# WIRELESS SENSORS IN THERMAL PROTECTION SYSTEMS

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## ABSTRACT

*The goal of the University of Idaho's ThermaSense team is to design, build, and test a Thermal Protection System (TPS) wireless sensor system that can be integrated into TPS materials on planetary entry probe missions. Currently if sensors are embedded within Thermal Protection Systems, the sensors must be fully wired to carry power, commands, and data from the sensors to a data collection system within the spacecraft. This current system adds unnecessary weight and has the potential to increase the flight risk. As a result sensors have not been frequently used. To save mass, complexity, and reduce risk, a fully wireless system has been designed and tested.*

*Several different wireless transmission methods were researched including radio frequency, infrared, and near field electromagnetic coupling. Preliminary results show that an RF transmitter was a reasonable choice, because there would not necessarily be line of sight for an IR transmitter and electromagnetic coupling is an underdeveloped technology. The RF protocol selected was ZigBee, a protocol used mostly by industry to transmit sensor network data for low power applications. To demonstrate proof of concept, a wireless TPS temperature measurement system comprising four thermocouples was designed, built, and tested at the NASA Ames X-jet facility. Tests were conducted using different RF transmitter antenna configurations, power settings, heat fluxes, and transmission distances. Test results showed that the wireless system could transmit out of the environment with little interference. There was some packet loss and other problems involved with the thermocouple bonding in the TPS but the transmission link was found to be strong.*

## 1. BACKGROUND

### 1.1. Overview

Every spacecraft entering a planetary atmosphere requires a Thermal Protection System (TPS). The TPS must endure severe heat loads, which requires an understanding of atmospheric properties, vehicle aerodynamics, TPS material properties and the physics of the entry environment. NASA and other space agencies would like to collect temperature, pressure, heat flux, radiation, and recession measurements on flight tests and flight missions in order to verify TPS design and to aid in the characterization of physical and chemical phenomena in the entry environment. Currently the missions that do fly with thermocouples have the sensors wired into the TPS of the spacecraft. Utilizing this architecture adds risk to the TPS system due to the process of routing wires in the shield and the difficulty of jettisoning the system after entry. Many current and past spacecraft engineers have decided not to fly sensors embedded within the TPS in an effort to mitigate the risk of spacecraft failure during entry. A wireless instrumentation system could collect measurements needed for scientists and engineers to improve future spacecraft design while lowering the overall risk of implementing sensors into the entry vehicles.

### 1.2. Problem Definition

NASA would like to develop a wireless sensor system for future atmospheric entry probes, and has asked the University of Idaho electrical and mechanical engineering senior design team, ThermaSense, to provide a preliminary proof of concept of a wireless system architecture. The design of the wireless sensor system is a multi-stage project spanning several years. ThermaSense's focus was to research and understand the current state of wireless transmission, and to develop a prototype wireless TPS sensor system. The project's main focus was on establishing wireless communication between the sensor and a computer for data acquisition with a secondary focus on the actual temperature sensor and the data acquisition. This project required ThermaSense to design a wireless system using off the shelf components and to create a table top demonstration that verified the success of the new wireless thermocouple system. To complete this goal the team researched the current state of wireless communication architecture and decided on specific components. Once designed and perfected the new wireless architecture could be extended to many other

different types of TPS mounted sensors such as accelerometers and pressure sensors.

## 1.3. Concepts Considered

A primary focus of this project was to research different types of wireless architectures that are available for use in a wireless system. With preliminary research of wireless and thermocouple architectures the team constructed a block diagram to express the outline of the transmitter sensor system as seen in Figure 1. Using Figure 1 as guidance, three main architectures were considered: radio frequency, light emission and near field magnetic communication. Before looking at each architecture within the context of the specific project scenario, the team researched and developed a decision matrix for each of the types of wireless transmission in order to develop an understanding of the capabilities and restraints.
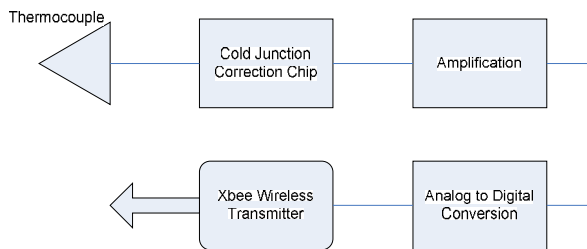


*Figure 1. Fundamental Transmitter Circuit Structure*

As seen in Table 1 the decision matrix evaluated each architecture by power consumption, data rate, transmission distance, necessity of line of sight, operating frequency, and overall complexity [1].

Using this decision matrix ThermaSense narrowed down the available wireless technologies to ZigBee [2] and IR [3], with the addition of Near Field Magnetic Coupling (NFMC) [4] Technology. These three technologies were then researched in depth and another decision matrix was constructed as seen in Table 2.

*Table 2. Final Wireless Technologies Decision Matrix*

|  | **Zigbee** | **NFMC** | **Led** |
|---|---|---|---|
| **Size** | comparable | comparable | comparable |
| **Power Consumption** | highest | medium, potentially none | medium |
| **Batteries** | 2 AA | 1 AA | 9 volt |
| **Complexity** | medium | high | medium |
| **Cost** | high | lowest | medium |
| **Availability** | high | none | medium |
| **Noise Immunity** | medium | high | high |

Based on these characteristics alone, each architecture is capable of transmitting the thermocouple signal for a table top demonstration in an interference free facility. This will not be the environment of the final product, so the team also judged the wireless architectures on noise immunity and power consumption. When looking at the requirements of these two specifications, near field magnetic communication is the best wireless option. But since one of the other previously specified restraints of the technology must be readily available and NFMC is not, the next best choice is ZigBee.

## 1.4. Concept Selection

Taking into consideration the specifications defined during the problem definition phase (shown in Table 3) and the results of our initial research, the circuit structure shown in Figure 1, was modified to look like the structure in the following Figure 2.

| Table 1. Decision Matrix For Different Wireless Technologies | | | | | |
|---|---|---|---|---|---|
|  | ZigBee | 802.11 | Bluetooth | Wireless USB | IR Wireless |
| Data Rate | 250 Kbits/s | 54 Mbits/sec | 1 Mbits/s | 62.5 Kbits/s | 20-40 Kbits/s 115 Kbits/s |
| Range | 10-100 meters | 50-100 meters | 10 meters | 10 meters | <10 meters (line of sight) |
| Networking Topology | Ad-hoc, peer to peer, star, or mesh | Point to hub | Ad-hoc, very small networks | Point to Point | Point to Point |
| Operating Frequency | 2.4 GHz | 2.4 and 5 GHz | 2.4 GHz | 2.4 GHz | 800-900 nm |
| Complexity | Low | High | High | Low | Low |
| Power Consumption | Very Low | High | Medium | Low | Low |
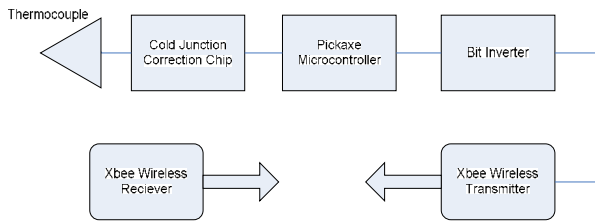
*Figure 2. Final Transmitter Circuit Structure*

*Table 3. Specifications for Prototype*

| Type | Specs |
|---|---|
| No. of Comm. Channels | 3 - 4 Channels |
| No. of Thermocouples | 3 - 4 Thermocouples |
| Sensor Placement | Center Embedded |
| Data Collection | Microsoft Excel |
| Data Rate | 1 Hz |
| Data Transfer | Real Time |
| Power Source | < 9 V |
| System Life Power | 2 years |
| Bandwidth | 1 – 10Hz |
| Temperature Resolution | +/- 5 degrees Celsius |
| Noise Interference | Medium Susceptibility |
| Temperature Range | 0 – 1000 degrees Celsius |
| Size | 13cm x 10cm x 2.5cm |
| Weight | 0.455 kg (Heat Shield Side) |
| Vibration | Low Susceptibility |
| Distance | 10 Meters |

The first change was the inclusion of four thermocouples instead of one connected to the circuit. With four thermocouples, the circuit met our specification and also better meets NASA's needs by giving them the ability to imbed more thermocouples into the TPS material.

In order to incorporate four thermocouples, ThermaSense also had to include four Cold Junction Correction (CJC) chips. It was decided that the CJC chip would also incorporate the amplification, A/D conversion, and the voltage to temperature calculations. This eliminated the amplifier and A/D converter shown in Figure 1 and also reduced the chance that noise could enter the system. No other changes were needed to the structure shown in Figure 1, after this change because the microcontroller has the ability to read 4 signals and pass them along to the transmitter.

## 2. PROTOTYPE AND TESTING

### 2.1. Prototype Description

The transmitter PCB is made up of seven IC's and four headers. Numbered, starting from top of

Figure 4 and Figure 5 there is first the terminal block (1). This terminal block is connected to four cold junction correction IC's (2). These IC's correct the voltage potential read coming in from the thermocouples connected to the terminal block for room temperature. The corrected temperature data is passed to the PicAxe microcontroller (3) using Serial Peripheral Interface (SPI) protocol. The PicAxe microcontroller converts the temperature data to the specified resolution and outputs the data to the bit inverter (4) using UART serial protocol. The bit inverter inverts the bits and feeds it to the MaxStream X-Bee ZigBee transceiver (5) [5]. The ZigBee transceiver transmits the temperature data wirelessly to the receiver connected to the computer. The receiver sends the temperature data down the USB cable and the software displays the temperature data on the screen.
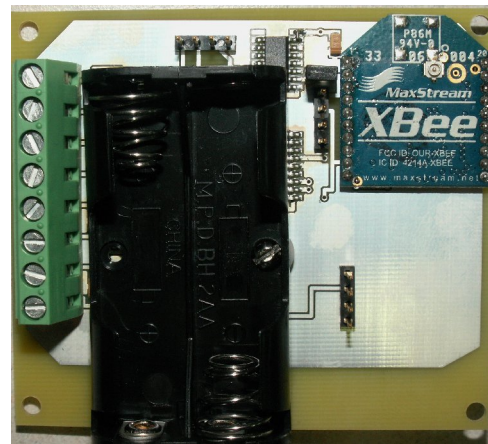


*Figure 3. Final Transmitter Prototype PCB*

Data acquisition software was written in Visual Basic 6.0, and the PicAxe microcontroller code was written in the PicAxe Programming editor. This editor can be downloaded from the PicAxe website. The PCBs were laid out in EAGLE Layout Editor, which is a free download from the Eagle layout website. The layout files are available from the ThermaSense website [6]. The circuit traces are shown in Figure 4 and Figure 5.
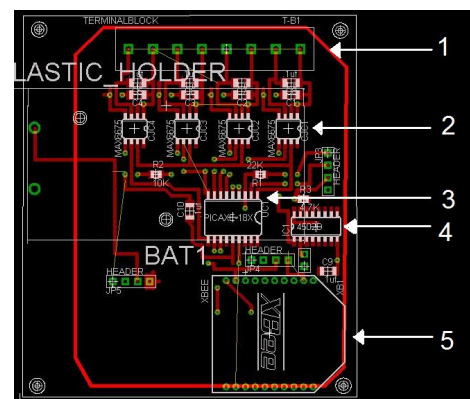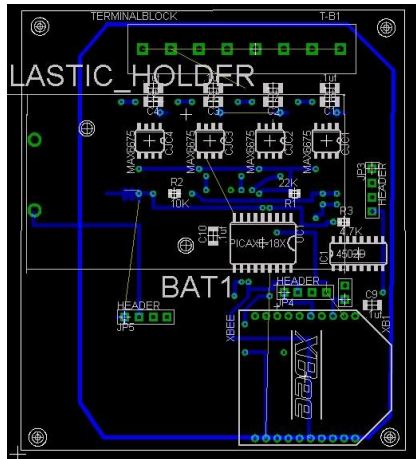


*Figure 4. Top PCB Layout*

*Figure 5. Bottom PCB Layout*

## 2.2 Sensor Calibration

The CJC chips are factory calibrated to be accurate to with-in +/- 4 degrees Celsius through the complete range of temperatures added to a +/- .2 percent reading error. Once the temperature data enters the CJC, the only other possible error in data received would be a dropped packet. To test the factory calibration a controlled test was set up and conducted.

A voltage from a DC source applied to the thermocouple inputs caused the circuit to display a temperature. Comparing this temperature against standard type K thermocouple tables provides an indication of the circuit calibration error. The results of the temperature calibration test and the accuracy of the circuit in a typical room environment are shown in Figure 6.
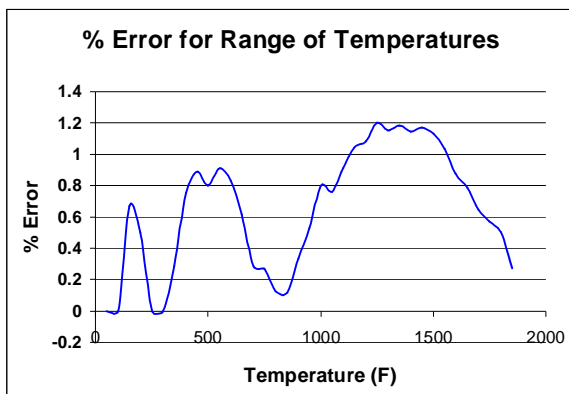


*Figure 6. Percent Error Found in Calibration Testing*

The temperature calibration test table shows a maximum error of +/- 1.2 percent error within the range of the temperatures to be read. This error is over the manufacturer's maximum rated error of +/- .8 percent error at maximum reading. There are several possible causes for the difference in maximum error. The first is the circuit layout. Because there is a terminal block connecting the CJC chip and the thermocouple, a voltage error due to the metal contacts is possible causing the circuit to read a slightly incorrect thermocouple voltage. The second is a programming error where the CJC reads off a temperature in Celsius and rounded off decimals turn into significant errors when converted to Fahrenheit. Both of these possibilities can be compensated for with the correct calibration precautions addressed in the code.

## 2.3 Entry Environment Testing

For proof of concept, testing was conducted in an X-Jet chamber at NASA Ames Research Center. The X-Jet consists of a vacuum chamber and plasma torch as the heat source. Four thermocouples were embedded at different depths of 2.0cm, 1.5cm, 1.0cm and 0.5cm in the LI-900 material as seen in Figure 7. The thermocouples were then attached to the wireless system to transmit back to the computer.
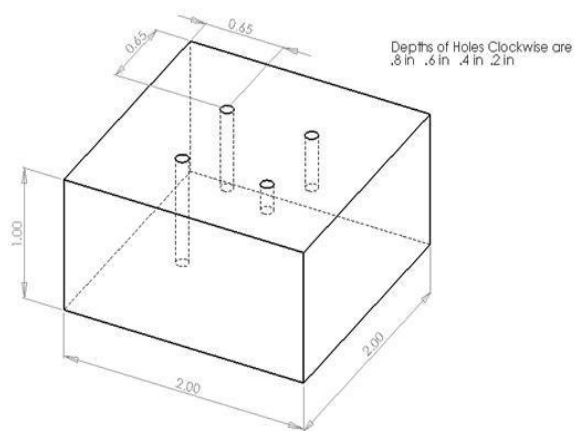


*Figure 7. LI-900 Thermocouple Layout*

Many tests were conducted at Ames X-Jet facility. Three antennas were tested; the PCB antenna, the whip antenna, and the external antenna. Power settings were also tested along with the antennas. The analysis of this test was based on packet loss and the predetermined specified distance of transmission. It was found that the best solution for the wireless transceivers was medium power with the whip antenna. The PCB antenna was found to need a high power setting to hold a strong signal. This was determined not to be worth the reward of saving the little space

compared to the whip antenna. The external antenna was also inadequate with predetermined size constraints. Since the whip antenna held a signal fine this is not a problem.

In addition, repeatability of the system was tested. Test 5 and 8 in the X-Jet were set up with the exact same test factors to test and demonstrate repeatability, these can be seen in Table 4. As can be seen in Figure 8, for this test, repeatability was verified.

| Torch Distance | 7 cm | Transmission Distance | 1.22 m |
|---|---|---|---|
| Antenna | PCB | Power setting | High |
| Calibration Run | Yes | Heat Flux From X-Jet | 117.51 W/cm$^2$ |
| Torch Start | 13 sec | Torch Stop | 45 sec |

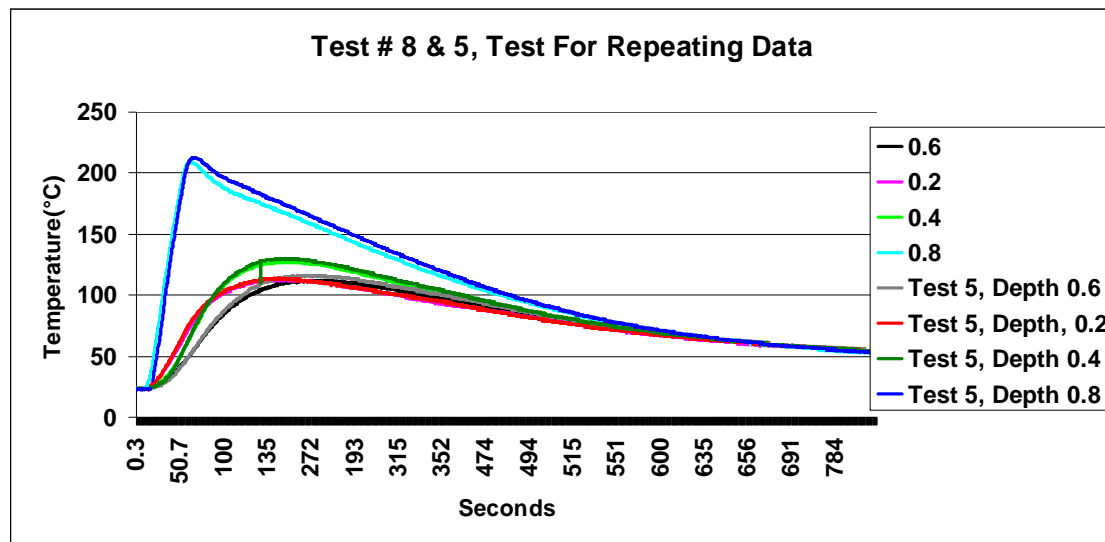*Table 4. Repeatability Test Set Up*



*Figure 8. X-Jet Repeatability Tests*

The small difference in readings is most likely due to the small change in properties of the LI-900 material after extreme heating. In conclusion, the wireless link was found to be strong with system recovery under heavy EMI noise, making the prototype a successful solution for wireless sensors.

## 3. RESULTS

The wireless TPS sensor system was initially specified to transmit data from the sensor to a data collection system once per second, to be powered by about 9 volts, and to have a system life of 2 years. The size of the system was specified to be 13cm x 10cm x 2.5cm and weigh 0.455kg. The system was specified to use thermocouple sensors attached to 3 – 4 communication channels. Temperatures recorded by the system were to be accurate to +/- 5 degrees Celsius.

Finally the system was required to have medium susceptibility to electromagnetic interference.

The ThermaSense team's final prototype recorded temperature data to the data collection system at a rate of ten Hz. The system in final design required 3.3 volts for operation; the team used two AA batteries to supply this energy. The current consumed by the system was measured to be 49 mA during continuous transmission. Given this measurement a rough estimate for system life expectancy is 8 hours. This time span obviously does not meet the system life specification. To overcome the issue the system can be programmed into sleep when not transmitting. The system only needs to transmit for five to six minutes and can be programmed into a sleep mode for the rest of the time, during which only a few micro amps will be consumed, resulting in a system that could roughly last five to six years. The final system weighs only 90.72 grams and is scaled to be 7.87cm x 7.37cm x 1.91cm. This size and weight is a large improvement over the original requirements.

The final prototype system included 4 thermocouple sensor communication channels. Calibration testing was completed outside an electrical interference environment using a precise mV source. The American Society for Testing and Materials (ASTM) table given for a type K thermocouple the mV source was used to compare measured temperature to ASTM standard. Calibration testing on the final system resulted in a +/- 1 percent temperature reading from the thermocouples. Electromagnetic interference testing was conducted at the NASA Ames X-Jet facility. The system transmitter was set for medium power using a whip antenna. These tests concluded that susceptibility to electromagnetic interference was low.

## 4. RECOMMENDED FUTURE WORK

Future work to be pursued by future teams includes creating a multi-nodal system, powering the sensor, programming the sensor for advanced power savings capabilities, determining the transmitter's interference tolerances, maximizing the signal to noise ratio while minimizing power consumption, miniaturization, multiple sensor instrumentation, and protective packaging of the transmitter system.

A future milestone of this project is to implement the wireless system on to a test flight. One possibility would be to fly as a payload on the University of Idaho's High Altitude Scientific balloon program. A successful flight test will require a software update. Currently, if the receiver gets corrupted data the software crashes and needs to be reset before data can be recorded. New software will need to overcome this issue as software will not be able to reset during a flight test and will also need to recover from lost packets and general signal disruption.

Further work also presents the need for multiple types of sensors to be used by means of the wireless system. This will require the transmitter circuit architecture to be universalized for all sensors, or separated form the ZigBee transmitter. If separation of the sensor circuitry and the transmitter is needed, work towards a standard transmitter circuit and a sensor connection strategy is recommended. This change would make it easier to connect the transmitter to any data source as long as that source transmits a standard set of data (time, sensor ID, and reading).

A successful flight test will also require improved protective packaging of the circuit. The environment that the circuit is exposed to during testing and flight is likely to involve thermal extremes, vibrations, and radiation. All of these factors could damage the circuit and disrupt the data. Packaging will need to be constructed that can resist these many environmental factors.

The discussed future work does not represent the only possibilities of continued research. It is expected that other issues, parameters, requirements and ideas will be uncovered as the project progresses. Any additional work that fits into the scope and propels the project towards the final goal of implementation on a space flight would be worthwhile and should be pursued.

## 5. CONCLUSION

The system designed by the University of Idaho ThermaSense team provides proof that ZigBee technology is a feasible solution to NASA's wired TPS sensor problem. ZigBee design goals for low power and low bandwidth were tested and achieved with the team's wireless TPS sensor system. Initial analysis shows integrating sleep mode into the design will allow for five to six years of operation from two AA batteries. ThermaSense's final prototype weighs 90.7 grams, reducing sensor system weight by an estimated 50 percent. Not only does this reduce the weight of the spacecraft carrying the system, but it also reduces space required for the system.

With the tested ability of the final prototype to overcome electromagnetic interference, the system will now be miniaturized and further developed by next year's senior design team. Using the thermocouple system as proof of concept, the wireless system should be expanded to all different types of sensors useful to embed within TPS material. Once these steps are complete the system can be flown on a probe mission to ensure performance and reliability.

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